34 Electric Current

Chapter 34 is divided into ten sections:

Chapter 34 uses the classical approach of comparing electric current with the flow of water in a pipe. Ohm's law, direct and alternating current, electric shock, the source and speed of electrons in a circuit, and electric power are also covered.

The last chapter discussed the concept of electric potential, or voltage. This chapter will show that voltage is an "electrical pressure" that can produce a flow of charge, or *current*, within a conductor. The flow is restrained by the *resistance* it encounters. When the flow takes place along one direction, it is called *direct current* (dc); when it flows to and fro, it is called *alternating current* (ac). The rate at which energy is transferred by electric current is *power*. You'll note here that there are many terms to be sorted out. This is easier (and more meaningful) to do when you have some understanding of the ideas these terms represent. In turn, the ideas are better understood if you know how they relate to one another. Let's begin with the flow of electric charge.

Stress that the meaning of these new terms is important to understanding this chapter. Each term is defined in more depth at the place in the chapter where it is first discussed.

34.1 Flow of Charge

Important Term

potential difference

Recall in your study of heat and temperature that heat flows through a conductor when a difference in temperature exists across its ends. Heat flows from the end of higher temperature to the end of lower temperature. When both ends reach the same temperature, the flow of heat ceases.

In a similar way, when the ends of an electrical conductor are at different electric potentials, charge flows from the higher potential to the lower potential. Charge flows when there is a **potential difference**, or difference in potential (voltage), across the ends of a conductor. The flow of charge will continue until both ends reach a common potential. When there is no potential difference, no flow of charge will occur.

As an example, if one end of a wire were connected to the ground and the other end placed in contact with the sphere of a

Van de Graaff generator charged to a high potential, a surge of charge would flow through the wire. The flow would be brief, however, for the sphere would quickly reach a common potential with the ground.

To attain a sustained flow of charge in a conductor, some arrangement must be provided to maintain a difference in potential while charge flows from one end to the other. The situation is analagous to the flow of water from a higher reservoir to a lower one (Figure 34–1 left). Water will flow in a pipe that connects the reservoirs only as long as a difference in water level exists. (This is implied in the saying, "Water seeks its own level.") The flow of water in the pipe, like the flow of charge in the wire that connects the Van de Graaff generator to the ground, will cease when the pressures at each end are equal. In order that the flow be sustained, there must be a suitable pump of some sort to maintain a difference in water levels (Figure 34–1 right). Then there will be a continual difference in water pressures and a continual flow of water. The same is true of electric current.

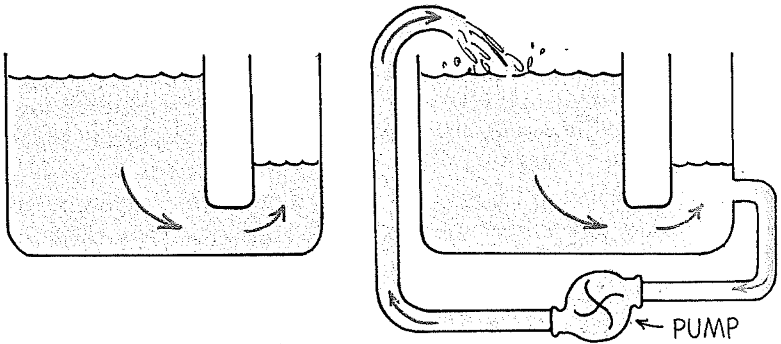

Fig. 34-1 (Left) Water flows from the reservoir of higher pressure to the reservoir of lower pressure. The flow will cease when the difference in pressure ceases. (Right) Water continues to flow because a difference in pressure is maintained with the pump.

34.2 Electric Current

Important Terms

ampere
electric current

Electric current is simply the flow of electric charge. In solid conductors, it is the electrons that carry the charge through the circuit. This is because the electrons are free to move throughout the atomic network. These electrons are called *conduction electrons*. Protons, on the other hand, are bound inside atomic nuclei that are more or less locked in fixed positions. In fluids, however, positive and negative ions as well as electrons may compose the flow of electric charge.

Electroplating is an example of flow of ions in a fluid.

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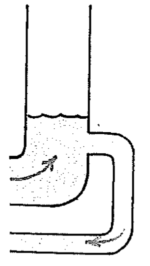

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Electric current is measured in **amperes**, symbol A.* An ampere is the flow of one coulomb of charge per second. (Recall that one coulomb, the standard unit of charge, is the electric charge of 6.25 billion billion electrons.) In a wire that carries a current of 5 amperes, for example, 5 coulombs of charge pass any cross section in the wire each second. So that's a lot of electrons! In a wire that carries 10 amperes, twice as many electrons pass any cross section each second.

Note that a current-carrying wire does not have a *net* electric charge. Negative electrons swarm through the atomic network that is composed of positively charged atomic nuclei. Under ordinary conditions, the number of electrons in the wire is equal to the number of positive protons in the atomic nuclei. So the net charge of the wire is normally zero at every moment.

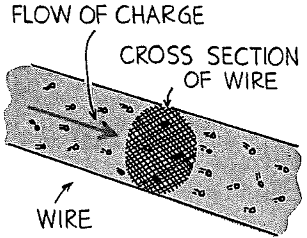

Fig. 34-2 When the rate of flow of charge past any cross section is one coulomb (6.25 billion billion electrons) per second, the current is one ampere.

34.3 Voltage Sources

Important Term

voltage source

Charges do not flow unless there is a potential difference. A sustained current requires a suitable "electrical pump" to provide a sustained potential difference. Something that provides a potential difference is known as a **voltage source**. If you charge a rubber rod by rubbing it with fur, you can develop a large voltage between the rod and the fur. This voltage source is not a good electrical pump because when the rod and the fur are connected by a conductor, the potentials equalize in a single brief surge of moving charges. It is not practical. Dry cells, wet cells, and generators, however, are capable of maintaining a steady flow. (A battery is just two or more cells wired together.)

Dry cells, wet cells, and generators supply energy that allows charges to move. In dry cells and wet cells, energy released in a chemical reaction that takes place inside the cell is converted to electric energy.** Generators convert mechanical energy to electric energy, as discussed in Chapter 37. The electric potential energy produced by whatever means is available at the terminals of the cell or generator. The potential energy per coulomb of charge available to electrons that move from one terminal to the other equals the potential difference (voltage) that provides the "electrical pressure" to move electrons through a circuit joined to these terminals.

Point out that voltage obtained from dry cells or wet cells is no different from that obtained from a generator. Also, the voltage from a generator using coal, oil, or nuclear fuel is the same.

The ampere is named in honor of André Marie Ampère (1775–1836), a French physicist.

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* The SI symbol for ampere is A. However, an older symbol still in common usage is amp. People often speak of a current of, say, "5 amps."

** A description of the chemical reactions inside dry cells and wet cells can be found in almost any chemistry textbook.

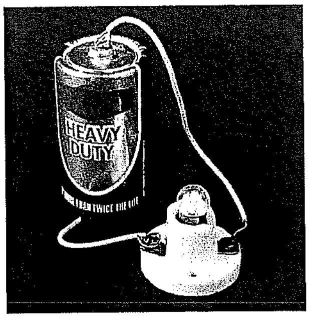

Fig. 34-3 Each coulomb of charge that is made to flow in a circuit that connects the ends of this 1.5-volt flashlight cell is energized with 1.5 joules.

Power utilities use electric generators to provide the 120 volts that is delivered to home outlets. The potential difference between the two holes in the outlet is 120 volts. When the prongs of a plug are inserted into the outlet, an electrical "pressure" of 120 volts is placed across the circuit connected to the prongs. This means that 120 joules of energy is supplied to each coulomb of charge that is made to flow in the circuit.

There is often some confusion between charge flowing *through* a circuit and voltage being impressed *across* a circuit. To distinguish between these ideas, consider a long pipe filled with water. Water will flow *through* the pipe if there is a difference in pressure *across* or between its ends. Water flows from the high-pressure end to the low-pressure end. Only the water flows, not the pressure. Similarly, you say that charges flow *through* a circuit because of an applied voltage *across* the circuit.* You don't say that voltage flows through a circuit. Voltage doesn't go anywhere, for it is the charges that move. Voltage causes current.

34.4 Electrical Resistance

Important Terms

electrical resistance
ohm

The amount of current that flows in a circuit depends on the voltage provided by the voltage source. It also depends on the resistance that the conductor offers to the flow of charge, or the **electrical resistance**. This is similar to the rate of water flow in a pipe, which depends not only on the pressure behind the water but on the resistance offered by the pipe itself. The resistance of a wire depends on the *conductivity* of the material (that is, how well it conducts) and also on the thickness and length of the wire.

Electrical resistance is less in thick wires. The longer the wire, of course, the greater the resistance. In addition, electrical resistance depends on temperature. The greater the jostling about of atoms within the conductor, the greater resistance the conductor offers to the flow of charge. For most conductors, increased temperature means increased resistance.** The resistance of some metals approaches zero at very low temperatures. These are the superconductors discussed briefly in Chapter 32.

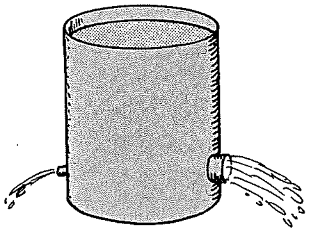

Fig. 34-4 For a given pressure, more water passes through a large pipe than a small one. Similarly, more electric current passes through a large-diameter wire than a small one.

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* It is conceptually simpler to say that current flows through a circuit, but don't say this around somebody who is "picky" about grammar, for the expression "current flows" is redundant. More properly, charge flows, which *is* current.

** Carbon is an interesting exception. At high temperatures, electrons are shaken from the carbon atom, which increases electric current. Carbon's resistance, in effect, lowers with increasing temperature. This behavior, along with its high melting temperature, accounts for the use of carbon in arc lamps.

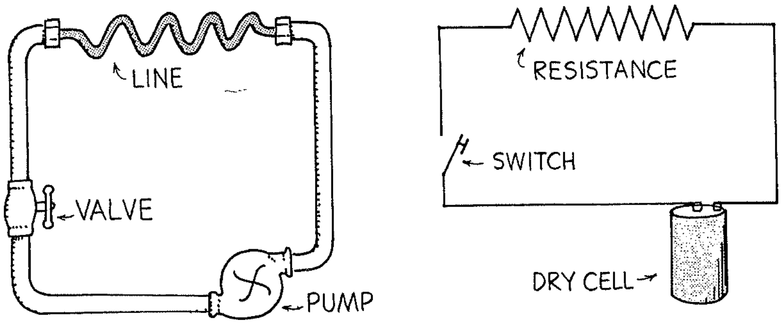

Fig. 34-5 Analogy between a simple hydraulic circuit and an electric circuit.

Electrical resistance is measured in units called ohms,* after Georg Simon Ohm, a German physicist who tested different wires in circuits to see what effect the resistance of the wire had on the current.

34.5 Ohm's Law

Important Term

Ohm's law

Ohm discovered that the amount of current in a circuit is directly proportional to the voltage impressed across the circuit, and is inversely proportional to the resistance of the circuit. In short,

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

This relationship between voltage, current, and resistance is called **Ohm's law**.**

The relationship between the units of measurement for these three quantities is:

$$1 \text{ ampere} = 1 \frac{\text{volt}}{\text{ohm}}$$

So for a given circuit of constant resistance, current and voltage are proportional. This means that you'll get twice the current for twice the voltage. The greater the voltage, the greater the current. But if the resistance is doubled for a circuit, the current will be half what it would be otherwise. The greater the resistance, the less the current. Ohm's law makes good sense.

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* The Greek letter omega (Ω) is usually used as a symbol for ohm.

** Many texts use V for voltage, I for current, and R for resistance, and express Ohm's law as $V = IR$. It then follows that $I = V/R$, or $R = V/I$, so if any two variables are known, the third can be found.

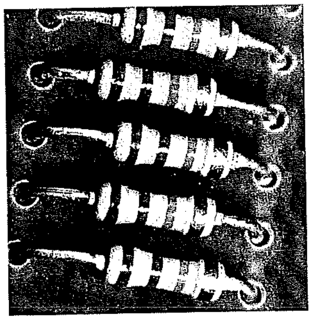

Fig. 34-6 Resistors. The stripes are color coded to indicate the resistance in ohms.

Using specific values, a potential difference of 1 volt impressed across a circuit that has a resistance of 1 ohm will produce a current of 1 ampere. If a voltage of 12 volts is impressed across the same circuit, the current will be 12 amperes.

The resistance of a typical lamp cord is much less than 1 ohm, while a typical light bulb has a resistance of about 100 ohms. An iron or electric toaster has a resistance of 15 to 20 ohms. The low resistance permits a large current, which produces considerable heat. Inside electrical devices such as radio and television receivers, the current is regulated by circuit elements called *resistors*, whose resistance may range from a few ohms to millions of ohms.

▸ Questions

1. What is the resistance of an electric frying pan that draws 12 amperes of current when connected to a 120-volt circuit?
2. How much current is drawn by a lamp that has a resistance of 100 ohms when a voltage of 50 volts is impressed across it?

34.6 Ohm's Law and Electric Shock

What causes electric shock in the human body—current or voltage? The damaging effects of shock are the result of current passing through your body. From Ohm's law, we can see that this current depends on the voltage applied, and also on the electrical resistance of the human body.

The resistance of your body depends on its condition and ranges from about 100 ohms if you're soaked with salt water to about 500 000 ohms if your skin is very dry. If you touched the

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▸ Answers

1. The resistance is 10 ohms.

   resistance = (voltage)/(current) = (120 volts)/(12 amperes) = 10 ohms

   An electrical device is said to *draw* current when voltage is impressed across it, just as water is said to be drawn from a well or a faucet. In this sense, to draw is not to attract, but to *obtain*.

2. The current is 0.5 ampere.

   current = (voltage)/(resistance) = (50 volts)/(100 ohms) = 0.5 ampere two electrodes of a battery with dry fingers, the resistance your body would normally offer to the flow of charge would be about 100 000 ohms. You usually would not feel 12 volts, and 24 volts would just barely tingle. If your skin were moist, on the other hand, 24 volts could be quite uncomfortable. Table 34–1 describes the effects of different amounts of current on the human body.

Table 34–1 Effect of Various Electric Currents on the Body

Current in amperes	Effect
0.001	Can be felt
0.005	Painful
0.010	Involuntary muscle contractions (spasms)
0.015	Loss of muscle control
0.070	Through the heart; serious disruption; probably fatal if current lasts for more than 1 second.

Electricians usually work "with one hand in their pocket"; that is to say, they use only one hand when there is any danger of a "hot wire." If they use two hands and there is a hot wire, the current will go from one hand to another across the chest and paralyze the heart.

▶ Questions

1. If the resistance of your body were 100 000 ohms, how much current would be produced in your body if you touched the terminals of a 12-volt battery?
2. If your skin were very moist so that your resistance was only 1000 ohms, and you touched the terminals of a 24-volt battery, how much current would you draw?

Many people are killed each year by current from common 120-volt electric circuits. If you touch a faulty 120-volt light fixture with your hand while your feet are on the ground, there is a 120-volt "electric pressure" between your hand and the ground. Resistance to current flow is usually greatest between your feet and the ground, so the current is usually not enough to do serious harm. But if your feet and the ground are wet, there is a low-resistance electrical bond between you and the ground.

▶ Answers

1. The current in your body would be:

$$\text{current} = (\text{voltage})/(\text{resistance}) = (12\ \text{V})/(100\ 000\ \Omega) = 0.00012\ \text{A}$$

2. You would draw (24 V)/(1000 Ω), or 0.024 A, a dangerous amount of current!

Your overall resistance is so lowered that the 120-volt potential difference across your body may produce a harmful current in your body.

Drops of water that collect around the on-off switch of devices such as a hair dryer can conduct current to the user. Although distilled water is a good insulator, the ions in ordinary water greatly reduce the electrical resistance. Dissolved materials, especially small amounts of salt, reduce the resistance even more. There is usually a layer of salt left from perspiration on your skin, which when wet lowers your skin resistance to a few hundred ohms or less. Handling electrical devices while taking a bath is extremely dangerous.

Fig. 34-7 Handling a wet hair dryer can be like sticking your fingers into a live socket.

You have seen birds perched on high-voltage wires. Every part of their bodies is at the same high potential as the wire, and they feel no ill effects. For the bird to receive a shock, there must be a *difference* in electric potential between one part of its body and another part. Current will then pass along the path of least electrical resistance connecting these two points.

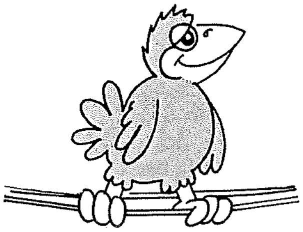

Fig. 34-8 The bird can stand harmlessly on one wire of high potential, but it had better not reach over and grab a neighboring wire! Why not?

Suppose you fell from a bridge and managed to grab onto a high-voltage power line, halting your fall. So long as you touch nothing else of different potential, you will receive no shock at all. Even if the wire is several thousand volts above ground potential and even if you hang by it with two hands, no charge will flow from one hand to the other. This is because there is no difference in electric potential between your hands. If, however, you reach over with one hand and grab onto a wire of different potential, ZAP!!

Mild shocks occur when the surfaces of electrical appliances are at a different electric potential from the surfaces of other nearby devices. If you touch surfaces of different potentials, you become the pathway to equilibrium. Sometimes the effect is more than mild. To prevent this problem, the outsides of electrical appliances are connected to a ground wire, which is connected to the round third prong of a three-wire electrical plug (Figure 34–9). All ground wires in all plugs are connected together through the wiring system of the house. The two flat prongs are for the current-carrying double wire, part of which is live and the other neutral. If the live wire accidentally comes in contact with the metal surface of an appliance, the current will be directed to ground rather than shocking you if you handle it.

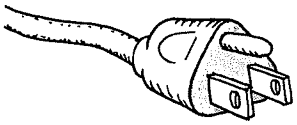

Fig. 34-9 The third prong connects the body of the appliance directly to ground. Any charge that builds up on an appliance is therefore conducted to the ground.

Electric shock overheats tissues in the body or disrupts normal nerve functions. It can upset the nerve center that controls breathing. In rescuing victims, the first thing to do is clear them from the electric supply with a wooden stick or some other nonconductor so that you don't get electrocuted yourself. Then apply artificial respiration.

▸ **Question**
What causes electric shock—current or voltage?

34.7 Direct Current and Alternating Current

Important Terms

alternating current
direct current

Electric current may be dc or ac. By *dc*, we mean **direct current**, which refers to a flow of charge that is *always in one direction*. A battery produces direct current in a circuit because the terminals of the battery always have the same sign of charge. Electrons always move through the circuit in the same direction, from the repelling negative terminal and toward the attracting positive terminal. Even if the current moves in unsteady pulses, so long as it moves in one direction only, it is dc.

Alternating current (ac) acts as the name implies. Electrons in the circuit are moved first in one direction and then in the opposite direction, alternating to and fro about relatively fixed positions. This is accomplished by alternating the polarity of voltage at the generator or other voltage source. Nearly all commercial ac circuits in North America involve voltages and currents that alternate back and forth at a frequency of 60 cycles per second. This is 60-hertz current. In some places, 25-hertz, 30-hertz, or 50-hertz current is used.

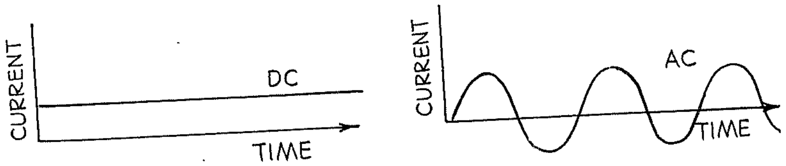

Fig. 34-10 Direct current (dc) does not change direction over time. Alternating current (ac) cycles back and forth.

The popularity of ac arises from the fact that electric energy in the form of ac can be transmitted great distances with easy voltage step-ups that result in lower heat losses in the wires. Why this is so will be discussed in Chapter 37.

The primary use of electric current, whether dc or ac, is to transfer energy quietly, flexibly, and conveniently from one place to another.

▸ **Answer**
Electric shock *occurs* when current is produced in the body, which is *caused* by an impressed voltage.

34.8 The Speed of Electrons in a Circuit

Stress that only the electric field, not the electrons, travels at the speed of light. Many students get this wrong on tests and so must have this wrong conceptually.

When you flip on the light switch on your wall and the circuit is completed, the light bulb appears to glow immediately. When you make a telephone call, the electrical signal carrying your voice travels through the connecting wires at seemingly infinite speed. This signal is transmitted through the conductors at nearly the speed of light. It is *not* the electrons that move at this speed but the signal.

At room temperature, the electrons inside a metal wire have an average speed of a few million kilometers per hour due to their thermal motion. This does not produce a current because the motion is random. There is no flow in any one direction. But when a battery or generator is connected, an electric field is established inside the wire. It is the electric field that travels through a circuit at nearly the speed of light. The electrons continue their random motions while simultaneously being nudged through the wire by the electric field.

The conducting wire acts as a guide or "pipe" to the electric field lines that are established at the voltage source (Figure 34–11). If the voltage source is dc, like the battery shown in Figure 34–11, the electric field lines are maintained in one direction in the conductor.

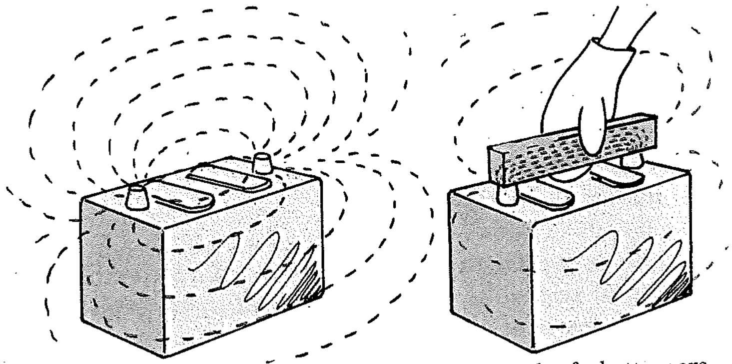

Fig. 34-11 The electric field lines between the terminals of a battery are directed through a conductor, which joins the terminals. A metal bar is shown here, but the conductor is usually an electric circuit.

Conduction electrons are accelerated by the field in a direction parallel to the field lines. Before they gain appreciable speed, they "bump into" the anchored metallic ions in their paths and lose some of their kinetic energy to them. This is why current-carrying wires become hot. These collisions interrupt the motion of the electrons so that their actual *drift speed*, or *net* *speed* through the wire due to the field, is extremely low. In a typical dc circuit, in the electrical system of an automobile, for example, electrons have a net average drift speed of about 0.01 cm/s. At this rate it would take more than three hours for an electron to travel through 10 meters of wire.

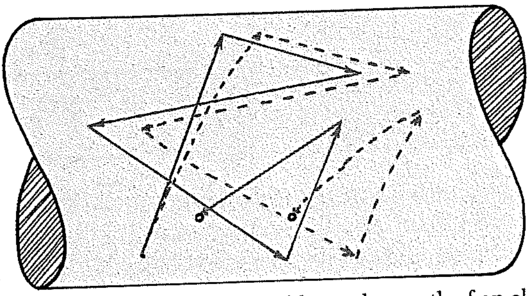

Fig. 34-12 The solid lines depict a possible random path of an electron bouncing off atomic nuclei in a conductor. Instantaneous speeds are about 1/200 the speed of light. The dashed lines show an exaggerated view of how this path may be altered when an electric field is applied. The electron drifts toward the right with an average speed much less than a snail's pace.

In an ac circuit, the conduction electrons don't go anywhere. They oscillate rhythmically to and fro about relatively fixed positions. When you talk to your friend on the telephone, it is the *pattern* of oscillating motion that is carried across town at nearly the speed of light. The electrons already in the wires vibrate to the rhythm of the traveling pattern.

34.9 The Source of Electrons in a Circuit

Some people think that the electrical outlets in the walls of their homes are a source of electrons. They think that electrons flow from the power utility through the power lines and into the wall outlets of their homes. This is not true. The outlets in homes are ac. Electrons do not travel through a wire in an ac circuit, but instead vibrate to and fro about relatively fixed positions.

When you plug a lamp into an outlet, *energy* flows from the outlet into the lamp, not electrons. Energy is carried by the electric field and causes vibratory motion of the electrons that already exist in the lamp filament. If 120 volts are impressed on a lamp, then 120 joules of energy are given to each coulomb of charge that is made to vibrate. Most of this electrical energy is transformed into heat while some of it takes the form of light. Power utilities do not sell electrons. They sell *energy*. *You* supply the electrons.

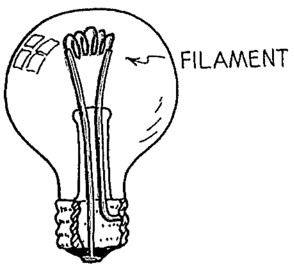

Fig. 34-13 The conduction electrons that surge to and fro in the filament of the lamp do not come from the voltage source. They are in the filament to begin with. The voltage source simply provides them with surges of energy.

Stress that only energy, not electrons, is supplied via the outlet; it is a common misconception.

Thus, when you are jolted by an electric shock, the electrons making up the current in your body originate in your body. Electrons do not come out of the wire and through your body and into the ground. Energy does. The energy simply causes free electrons in your body to vibrate in unison. Small vibrations tingle. Large vibrations can be fatal.

34.10 Electric Power

Important Term

electric power

When a charge moves in a circuit, it does work. Usually this results in heating the circuit or in turning a motor. The rate at which work is done, that is, the rate at which electric energy is converted into another form such as mechanical energy, heat, or light is called **electric power**. Electric power is equal to the product of current and voltage.*

$$\text{electric power} = \text{current} \times \text{voltage}$$

If the voltage is expressed in volts and the current in amperes, then the power is expressed in watts. So in units form,

$$1 \text{ watt} = (1 \text{ ampere}) \times (1 \text{ volt})$$

If a lamp rated at 120 watts operates on a 120-volt line, you can see that it will draw a current of 1 ampere, since 120 watts = (1 ampere) × (120 volts). A 60-watt lamp draws 0.5 ampere on a 120-volt line. This relationship becomes a practical matter when you wish to know the cost of electrical energy, which varies from 1 cent to 10 cents per kilowatt-hour depending on locality.

A *kilowatt* is 1000 watts, and a *kilowatt-hour* represents the amount of energy consumed in 1 hour at the rate of 1 kilowatt.**

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* Note that this follows from the definitions of current and voltage:

$$\text{current} \times \text{voltage} = \frac{\cancel{\text{charge}}}{\text{time}} \times \frac{\text{energy}}{\cancel{\text{charge}}} = \frac{\text{energy}}{\text{time}} = \text{power}$$

** Since power = (energy)/(time), simple rearrangement gives energy = power × time; hence, energy can be expressed in units of kilowatt-hours.

Physicists measure energy in *joules*, but utility companies customarily sell energy in units of *kilowatt-hours* (kW·h), where 1 kW·h = 3.6×10^6 J. This duplication of units added to an already long list of units unfortunately makes the study of physics more difficult. It will be enough for you to become familiar with and be able to distinguish between the units *coulombs*, *volts*, *ohms*, *amperes*, *watts*, *kilowatts*, and *kilowatt-hours* here. Mastering them requires laboratory work and the help of more advanced textbooks. An understanding of electricity takes considerable time and effort, so be patient with yourself if you find this material difficult.

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Therefore, in a locality where electric energy costs 5 cents per kilowatt-hour, a 100-watt electric light bulb can be run for 10 hours at a cost of 5 cents, or a half cent for each hour. A toaster or iron, which draws more current and therefore more power, costs several times as much to operate for the same time.

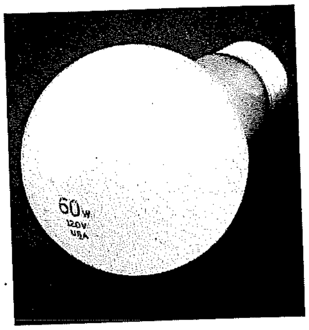

Fig. 34-14 The power and voltage on the light bulb read "60 W 120 V." How much current in amperes will flow though the bulb?

The current through the bulb will be
(60 W)/(120 V) = 0.5 A

▶ **Questions**

1. How much power is used by a calculator that operates on 8 volts and 0.1 ampere? If it is used for one hour, how much energy does it use?
2. Will a 1200-watt hairdryer operate on a 120-volt line if the current is limited to 15 amperes by a safety fuse? Can two hairdryers operate on this line?

▶ **Answers**

1. Power = current × voltage = (0.1 A) × (8 V) = 0.8 W. If it is used for one hour, then energy = power × time = (0.8 W) × (1 h) = 0.8 watt-hour, or 0.0008 kilowatt-hour.
2. One 1200-watt hairdryer can be operated because the circuit can provide (15 A) × (120 V) = 1800 watts. But there is inadequate power to operate two hairdryers of combined power 2400 watts. This can be seen also from the amount of current involved. Since 1 watt = (1 ampere) × (1 volt), note that (1200 watts)/(120 volts) = 10 amperes; so the hair dryer will operate when connected to the circuit. But two hairdryers on the same plug will require 20 amperes and blow the fuse.